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Novel single photon sources for new generation of quantum communications

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14. ABSTRACT
This project aimed to develop ideal single photon sources that will be used as building blocks for quantum cryptography and quantum key distribution There were numerous important achievements for the projects in the field of discovery of new technologically important single photon emitters in gallium nitride, boron nitride, silicon carbide and diamond. Weve established a library of emitters and characterized their optical properties for practical uses. There was also a review written on the topic of solid state single photon sources that was published in Nature Photonics in October 2016.

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Summary: This project aimed to develop ideal single photon sources that will be used as building blocks for quantum cryptography and quantum key distribution There were numerous important achievements for the projects in the field of discovery of new technologically important single photon emitters in gallium nitride, boron nitride, silicon carbide and diamond. We've established a "library" of emitters and characterized their optical properties for practical uses. There was also a review written on the topic of solid state single photon sources that was published in nature photonics in October 2016.

Introduction: The goal of this project was engineering new quantum emitters in the infrared that operate at room temperature. We also planned to explore new materials for generation of triggered single photon sources. The outcomes of the project will establish a new generation of building blocks for communication channels and enable absolutely secured information transfer between distant nodes – key prerequisite for quantum cryptography.

Experiment: the experimental work in this project spans materials science and spectroscopy:
Spectroscopy – we used a confocal microscope with various excitation lasers in both continuous and triggered modes. The single photon emission was analysed using confocal scanning combined with Hunbry Brown and Twiss interferometer equipped with single photon detectors. Measurements were done at room temperature and cryogenic temperatures, and polarization, lifetime and intensity were recorded.
Emitters engineering – we used ion implantation and electron beam irradiation under different gaseous environments to fabricate single emitters. We also used various annealing treatments in vacuum and under forming gas flow to induce the luminescent defects.

Results and Discussion: In accord with the goals of the project, the results included discoveries of new single photon emitters in various materials and their characterization. The details are given below, under each publication. The main overarching topic was establishing hexagonal boron nitride as a promising platform for quantum emitters. We developed means to increase their density, developed basic methods to engineer them, and demonstrate coupling to photonic and plasmonic resonators.

List of Publications and Significant Collaborations that resulted from your AOARD supported project: In standard format showing authors, title, journal, issue, pages, and date, for each category list the following:

a) papers published in peer-reviewed journals

1. **I. Aharonovich**, D. Englund and M. Toth "Solid state single photon emitters" Nature Photonics 10, 631 (2016); **cover image**
This is an invited review to write a road map for quantum technologies, focusing on the use of solid state quantum emitters. The review summarizes the state of the art and provides vision of the

next phase of research into quantum emitters. the review was highlighted on the cover of the October issue of Nature Photonics.

2. A. Berhane, K. Jeong, Z. Bodrog, S. Fiedler, T. Schröder, N. Triviño, T. Palacios, A. Gali, M. Toth, D. Englund and I. Aharonovich "Bright Room-Temperature Single Photon Emission from Defects in Gallium Nitride" Advanced Materials 29, 1605092 (2017)
   This work reports on the first room temperature single emitters in gallium nitride. The significance of this work lies in the fact that GaN is a comerically viable material, and therefore large scale wafers are easy to get. Electrical excitation may also be possible due to availability of p type and n type materials.

3. T. Tran, D. Wang, Z. Xu, A. Yang, M. Toth, T. W. Odom, **I. Aharonovich** *"Deterministic Coupling of Quantum Emitters in 2D Materials to Plasmonic Nanocavity Arrays"* Nano Letters 17, 2634, (2017)
   This is the first report on coupling single emitters in 2D materials to plasmonic lattices. Enhancement of two was observed and this work opens up new opportunities for integrated photonics and plasmonics.

4. A. Schell, H. Takashima, T. Tran, **I. Aharonovich** and S. Takeuchi *"Coupling quantum emitters in 2D materials with tapered fibers"* ACS Photonics 4, 761 (2017)
   Integration of single emitters with tapered fibers – first step towards hybrid photonic networks, where single emitters are coupled into fibers. First step towards scalable nanophotonics circuits with 2D materials. The approach can also be extended to remote sensing.

5. M. Kianinia, B. Regan, S. Tawfik, B. Regan, T. Tran, M. J. Ford, **I. Aaronovich**, and M. Toth, *"Robust Solid-State Quantum System Operating at 800K"* ACS Photonics, 4, 768 (2017) ***cover image***
   This is an interesting work showing that the emitters in hBN can operate at extreme temperatures of up to 800K. This is the hottest single photon emitter known to date. This is again highly advantageous for new sensing regimes where fluorescence can be used at extreme conditions where other materials fail.

6. Y. Zhou, A. Rasmita, K. Li, Q. Xiong, I. Aharonovich, W. Gao *"Coherent control of a strongly driven silicon vacancy optical transition in diamond"* **Nature Communications** 8, 14451, (2017)
   This work reports on a controlled coherent manipulation of a silicon vacancy color center in a nanodiamond. We demonstrate ultra fast coherent control of a photon, that makes this defect suitable for quantum information

7. T. Tran, S. Choi, C. Zheng, G. Seniutinas, A. Bendavid, M. Fuhrer, M. Toth and **I. Aharonovich** *"Room temperature single photon emission from oxidized tungsten disulphide multilayers"* Adv. Opt. Mater 5, 1600939 (2017)

   Discovery of new emitters in other 2D materials – namely tungsten disulphide. We found that after oxidation, there is a phase transition to tungsten oxide that has larger bandgap, and thus hosts emitters. Follow up works are currently on the way.

8. S. Choi, T. Tran, C. ElBadawi, C. Lobo, X. Wang, S. Juodkazis, G. Seniutinas, M. Toth, **I. Aharonovich** *"Engineering and localization of quantum emitters in large hexagonal boron nitride layers"* ACS Appl. Mater. Interf. (2016)

This work reports on observation of single emitters in large exfoliated hBN flakes. The uniqueness about this work is the fact that all emitters are localized at the edges or grain boundaries of the large flakes. This work is in fact raises a lot of questions about the origin of these emitters – and will be focus of future works on hBN

9. T. Tran, C. Elbadawi, D. Totonjian, C. Lobo, G. Grosso, H. Moon, D. Englund, M. Ford, **I. Aharonovich,** and M. Toth *"Robust Multicolor Single Photon Emission from Point Defects in Hexagonal Boron Nitride"* ACS Nano 10, 7331 (2016)

The work reports on the first multicolor emission from monolayers and multilayers hBN. It also shows nanofabrication of the emitters using electron beams and basic cryogenic measurements of the emitters.

10. B. Lienhard, T. Schröder, S. Mouradian, F. Dolde, T. Tran, **I. Aharonovich**, D. R Englund **"***Bright and stable visible-spectrum single photon emitter in silicon carbide"* Optica 3, 768 (2016)

This work reports on a new class of ultra bright emitters in silicon carbide. The emitters operate at visible spectral range and are ultra bright with full polarization properties. They are promising for integration with single crystal silicon carbide cavities.

11. A. Schell, T. Tran, H. Takashima, S. Takeuchi, **I. Aharonovich**, *"Non-linear excitation of quantum emitters in two-dimensional hexagonal boron nitride"* APL Photonics, 1, 091302 (2016)

This work reports that the emitters in hBN can be excited using a higher energy via two photon process. This work is important for two reasons – first, it makes the emitters suitable as markers for biological applications since exciation with infra red source inhibits autoflourescence. Second – it means the emitters can sustain very high power pulsed excitation sources.

12. T. Tran, C. Zachreson, A. Berhane, K. Bray, R. Sandstrom, L.-H. Li, T. Taniguchi, K. Watanabe, **I. Aharonovich**, and M. Toth *"Quantum Emission from Defects in Single-Crystalline Hexagonal Boron Nitride"* Phys. Rev. Applied 5, 034005 (2016)

This work reports on single emitters in bulk hexagonal boron nitride. It is the enabler of a range of follow up works with exfoliated hBN flakes. Exfoliated hBN flakes are required for controlled manipulation of the emitters, their positioning on various photonic cavities and engineering of emitters using ion implantation techniques.

e) we interacted with Dr Luke Bissell (AFRL) on the topic of single emitters. We maintain close interaction on the topics of growth of single digit nanodiamonds (performed in AFRL) and characterization of new single emitters. I visited AFRL in 2016, and Luke visited Australia in 2016 as well. We also recently met and discussed several projects during Spring MRS meeting in Phoenix. The division director, Dr Augustine Urbas, visited our group during beginning of 2017 and met with my students at UTS.

DD882: As a separate document, please complete and sign the inventions disclosure form. Put n/a in boxes 5 a/b if no inventions resulted from the research.

No patents were lodged during this work.